Kinematics of nearby OB3 stars with interstellar CaII line distances

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We tested the distances derived from the equivalent widths of interstellar CaII spectral lines by Megier et al. 2009. To this end, we used a sample of nearby 126 young OB3 stars ($r < 1$ kpc) with known proper motions and line-of-site velocities. It is shown that these stars are tightly bounded with the Gould Belt structure. Most part of this sample (about 100 stars) show the same kinematics as the sample of distant OB3 stars. Their galactocentric radial velocities are in good agreement with the following spiral density wave parameters: amplitude of radial perturbations $f_R \approx 12$ km/s, wavelength $\lambda \approx 2.3$ kpc and phase of the Sun in spiral wave $\chi_\odot \approx -90°$. But we revealed 20 stars with absolutely unusual kinematical features. Their galactocentric radial velocities show a wave, biased on $\approx 180°$ with respect to the wave, found from the whole sample. The idea of superposition of two spiral patterns seems to be probable.

1 Introduction

For study of Galactic kinematics various data are used. These are line-of-site velocities of HI and HII clouds with distances obtained using terminal-velocity procedure (Clemens 1985; McClure-Griffiths & Dickey 2007; Levine, Heiles & Blitz 2008); cepheids with a distance scale based on a period-luminosity relation, open star clusters and OB associations with photometric distances (Mishurov & Zenina 1999; Mel'nik, Dambis & Rastorguev 2001; Zabolotskikh, Rastorguev & Dambis 2002; Bobylev, Bajkova & Stepanishchev 2008; Mel'nik & Dambis 2009); masers with high-precision VLBI trigonometric parallaxes (Reid et al. 2009; McMillan & Binney 2010; Bobylev & Bajkova 2010; Bajkova & Bobylev 2012).

The most young massive stars of high luminosity (OB stars) are of great interest for the kinematics connected with Galactic spiral density wave study, because these stars were not able to withdraw from their birth places during their life time and therefore are good tracers of Galactic spiral structure.

The recent work by Bobylev & Bajkova (2011) was devoted to study of Galactic kinematics using distant OB3 stars ($r < 1$ kpc) with distances estimated with accuracy $\approx 15\%$ by Megier, Strobel & Galazutdinov (2009) from absorption lines of interstellar CaII. Note that for majority of these OB3 stars such high-precision estimates were obtained for the first time, taking into account that HIPPARCOS (1997) trigonometric parallaxes for them are not significant.

Nearby OB3 stars are of great interest for our tasks too. As can be seen from fig. 6 from Megier et al. (2009), and fig. 1 from Bobylev & Bajkova (2011), for stars with $r < 1$ kpc, the distances obtained from lines of interstellar CaII, are in good agreement with the estimates obtained using different methods.

This work is devoted to analysis of sample of nearby stars with distances ($r < 1$ kpc from Megier et al. (2009) list for study of kinematic peculiarities of Galactic spiral structure and the Gould Belt stars.

2 Data

For OB3 stars from Megier et al. (2009) list we took line-of-site velocities from CRVAD-2 compilation (Kharchenko et al. 2007) and proper motions from improved version of HIPPARCOS catalog (van Leeuwen 2007). For spectral-double stars the comparison with data base SB9 (Pourbaix, Tokovinin & Batten 2004) has been done to revise values of systemic line-of-site velocities V_γ. Line-of site velocities were significantly corrected for a number of stars from CRVAD-2 catalog. The whole sample consists of 258 HIPPARCOS stars with known distances, line-of-site velocities and proper motions including both distant and nearby stars. Sample of nearby stars ($r < 1$ kpc), which is of our interest, consists of 126 stars.

3 Method and basic relations

From observations we have heliocentric line-of-sight velocity V_r in $\mathrm{km\,s^{-1}}$; proper motion velocity components

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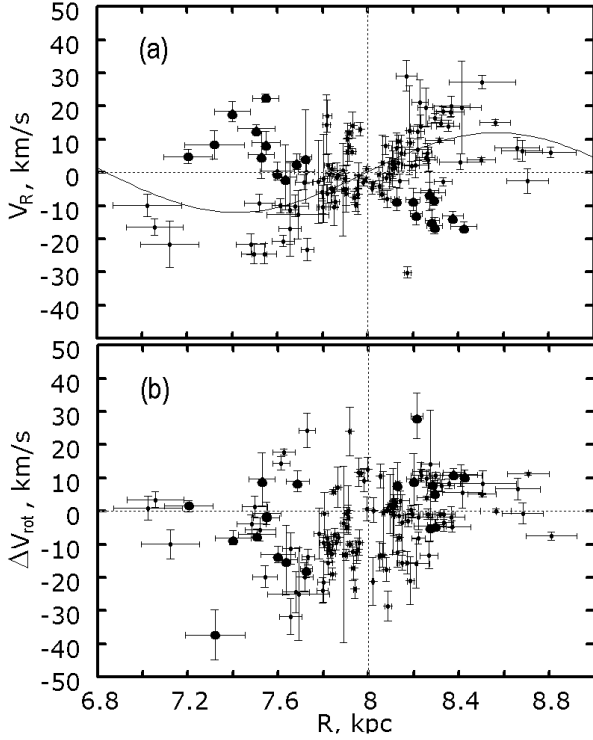
Fig. 1 Galactocentric radial V_R velocities of 126 stars vs R (a); residual rotational velocities ΔV_{rot} (b); vertical dotted line denotes location of the Sun.

Table 1 HIPPARCOS numbers of the OB3 stars marked in fig. 1 by black circles.

20234	23972	31088	32385	34561	35412
36778	40328	66925	80569	82110	86768
87812	87768	88331	88886	94385	94827
96483	117810				

$V_l = 4.74 r \mu_l \cos b$ and $V_b = 4.74 r \mu_b$ in the l and b directions, respectively (the coefficient 4.74 is the quotient of the number of kilometers in astronomical unit by the number of seconds in a tropical year); heliocentric distance r in kpc for a star. Proper motion components $\mu_l \cos b$ and μ_b are measured in $\mathrm{mas\,yr^{-1}}$. We adopt that $R_0 = 8.0 \pm 0.4$ kpc is the galactocentric distance of the Sun (Foster & Cooper, 2010).

Components of spatial velocities U, V, W of the stars are determined from observed line-of-sight and tangential velocities in the following way:

$$
\begin{aligned}
U &= V_r \cos l \cos b - V_l \sin l - V_b \cos l \sin b, \\
V &= V_r \sin l \cos b + V_l \cos l - V_b \sin l \sin b, \\
W &= V_r \sin b + V_b \cos b.
\end{aligned} \tag{1}
$$

Velocity U is directed towards the Galactic Centre, V along the Galactic rotation, and W towards the Northern Galactic pole.

Two projections of these velocities: V_R, directed radially from the Galactic Centre towards an object, and V_{rot}, orthogonal to V_R and directed towards Galactic rotation, are found from the following relations:

$$
\begin{aligned}
V_{rot} &= U \sin \theta + (V_0 + V) \cos \theta, \\
V_R &= -U \cos \theta + (V_0 + V) \sin \theta,
\end{aligned} \tag{2}
$$

where $V_0 = |R_0 \Omega_0|$, and position angle θ is determined as $\tan \theta = y/(R_0 - x)$, where x, y are Galactic Cartesian coordinates of an object. The quantity Ω_0 is the Galactic angular rotational velocity at distance R_0, parameters $\Omega_0^1, \ldots, \Omega_0^n$

are derivatives of the angular velocity from the first to the n-th order, respectively.

In addition, it is assumed that velocities U and V are free from the Solar velocity with respect to mean group velocity $(U_\odot, V_\odot, W_\odot)$. According to Schönrich, Binney & Dehnen (2010) $(U_\odot, V_\odot, W_\odot)_{\mathrm{LSR}} = (11.1, 12.2, 7.3) \pm (0.7, 0.5, 0.4)\ \mathrm{km\,s^{-1}}$.

According to linear theory of density waves (Lin & Shu 1964)

$$
\begin{aligned}
V_R &= -f_R \cos \chi, \\
\Delta V_{rot} &= f_\theta \sin \chi,
\end{aligned} \tag{3}
$$

where

$$
\chi = m[\cot(i) \ln(R/R_0) - \theta] + \chi_\odot \tag{4}
$$

is phase of the spiral wave (m is number of spiral arms, i is pitch angle, $\chi_\odot$ is the radial phase of the Sun in the spiral wave; f_R and f_θ are amplitudes of radial and tangential components of the perturbed velocities which, for convenience, are always considered positive. The distance R of an object from the Galactic rotation axis is calculated as

$$
R^2 = r^2 \cos^2 b - 2R_\circ r \cos b \cos l + R_\circ^2. \tag{5}
$$

In work by Bobylev & Bajkova (2011) using 102 distant OB3 stars from Megier et al. (2009) list, on the basis of Bottlinger kinematic equations, adopting $R_0 = 8$ kpc we found components of the solar peculiar velocity

$$
(u_\odot, v_\odot, w_\odot) = (8.9, 10.3, 6.8) \pm (0.6, 1.0, 0.4)\ \mathrm{km s^{-1}},
$$

galactic rotation parameters

$$
\begin{aligned}
\Omega_0 &= -31.5 \pm 0.9,\ \mathrm{km\,s^{-1}\,kpc^{-1}}, \\
\Omega_0' &= +4.49 \pm 0.12,\ \mathrm{km\,s^{-1}\,kpc^{-2}}, \\
\Omega_0'' &= -1.05 \pm 0.38,\ \mathrm{km\,s^{-1}\,kpc^{-3}},
\end{aligned} \tag{6}
$$

amplitudes of spiral density wave

$$
\begin{aligned}
f_R &= -12.5 \pm 1.1,\ \mathrm{km s^{-1}}, \\
f_\theta &= 2.0 \pm 1.6,\ \mathrm{km s^{-1}},
\end{aligned}
$$

pitch angle for two-armed spiral structure

$$
i = -5.3° \pm 0.3°,
$$

wavelength

$$
\lambda = 2.3 \pm 0.2\ \mathrm{kpc},
$$

the radial phase of the Sun in the spiral wave

$$
\chi_\odot = -91° \pm 4°.
$$

Having rotational parameters (6) it is easy to construct Galactic rotational curve and calculate residual rotational velocities ΔV_{rot}.

4 Results

In fig. 1 galactocentric radial velocities V_R (a) and residual rotational velocities ΔV_{rot} (b) are shown for 126 OB3 stars from the Solar neighborhood $r < 1$ kpc vs galactocentric distances R. The harmonic curve, shown in the top diagram, is a result of analysis of 102 distant OB3 stars (see solution (6)), having amplitude of radial perturbations $f_R = 12.5$ km s^{-1} and radial phase of the Sun in spiral density wave $\chi_\odot = -91°$. As it is seen from the picture this harmonic curve is fitted quite well to the majority of the stars of our sample. But there is a surprising group of 20 stars, marked by black circles, which distribution on the diagram is strongly different. As for residual rotational velocities (picture (b)) these stars does not show any peculiarities. So, peculiarities are seen only in radial velocities diagram. The Hipparcos numbers of marked unusual stars are given in table 1.

In fig. 2 the distribution of our 126 stars is shown in three galactic planes. From analysis of these diagrams we can conclude, in the first place, that the stars of our sample are tightly bounded with the Gould Belt structure. This conclusion follows from a characteristic inclination of the star system $\approx 17°$ to Galactic plane XY (Bobylev 2006), what is apparent from the middle diagram (b). In the second place, distribution of marked 20 stars is not distinguished from distribution of other stars.

The analysis presented here allows us to make an important conclusion that galactocentric radial velocities (V_R) of the Gould Belt stars are quite compatible with the galactic spiral density wave parameters found from data on distant stars.

The most interesting question is related to the nature of group of 20 marked stars. We put forth two possibilities:

1.There exist two spiral waves with almost equal amplitudes, but shifted each other by phase $\Delta\chi_\odot \approx 180°$. Similar composite models are known in literature, for example, a model 2+4, supposing existence in the Solar neighborhood simultaneously of two- and four-armed spiral structures (Lépine, Mishurov & Dedikov 2001; Mishurov & Acharova 2011).

2.Distances of these 20 stars are measured with large errors, caused by non-homogeneities in distribution of interstellar CaII clouds in the nearest Solar neighborhood connected with the Local Bubble. Here the variation of volume density of CaII ions attains 10 times under mean volume density $n_{CaII} \sim 10^{-9}$ $^{-3}$, and size of spatial non-homogeneities are ≈ 60 pc (Welsh et al. 2010).

We tried to eliminate the peculiarities in distribution of these 20 stars by decreasing their distances using different scaling coefficients Ks: $r_{new} = r \cdot Ks$. For a number of stars listed in table 1 the trigonometric parallaxes are determined with small errors ($\sigma_\pi/\pi < 10\%$) and corresponding trigonometric distances are about a half of distances determined using CaII scale. Therefore firstly we adopted $Ks = 0.5$, but scaling by this coefficient did not

change significantly the character of distribution. Only if $Ks = 0.2 - 0.1$, the peculiarities can be eliminated almost totally. But such value of Ks seems to be unrealistic.

The first possibility seems to be more probable. To test it we formed a new sample of 147 HIPPARCOS stars of spectral classes O–B2.5, which trigonometric parallaxes are determined with errors $\sigma_\pi/\pi \leq 10\%$ and line-of-site velocities from CRVAD-2 catalog (Kharchenko et al. 2007). Note that these stars have the most reliable distances. Galactocentric radial velocities V_R of these stars are shown in fig. 3 together with the same harmonic curve shown in fig. 1 (a). Note that in fig. 3 there are a few stars from table 1. Although we can not make some definite conclusions from fig. 3, all the same we can see a weak indicator of the presence of the second spiral pattern. Obviously, this problem requires further investigation.

5 Conclusions

We tested the distances derived from the equivalent widths of interstellar CaII spectral lines by Megier et al. To this end, we used a sample of nearby ($r < 1$ kpc) 126 young OB3 stars with known proper motions and line-of-site velocities. It is shown that these stars are tightly bounded with the Gould Belt structure.

We found that Galactic spiral density wave parameters obtained from the galactocentric radial velocities (V_R) of about 100 stars of our sample are in good agreement with ones obtained recently from sample of distant OB3 stars showing a wave with amplitude $f_R \approx 12$ km/s, wavelength $\lambda \approx 2.3$ kpc and phase of the Sun in spiral wave $\chi_\odot \approx -90°$.

We revealed 20 stars with absolutely unusual kinematical features. Their galactocentric radial velocities (V_R) show a wave, biased on $\approx 180°$ with respect to the wave, found from the whole sample. We proposed two hypothesis for discussion: 1)superposition of two spiral patterns; 2)errors in distances determined from the equivalent widths of interstellar CaII spectral lines are caused by non-homogeneity in distribution of interstellar CaII clouds in the nearest Solar neighborhood connected with the Local Bubble. But the first idea of superposition of two spiral patterns seems to be the more probable requiring further study.

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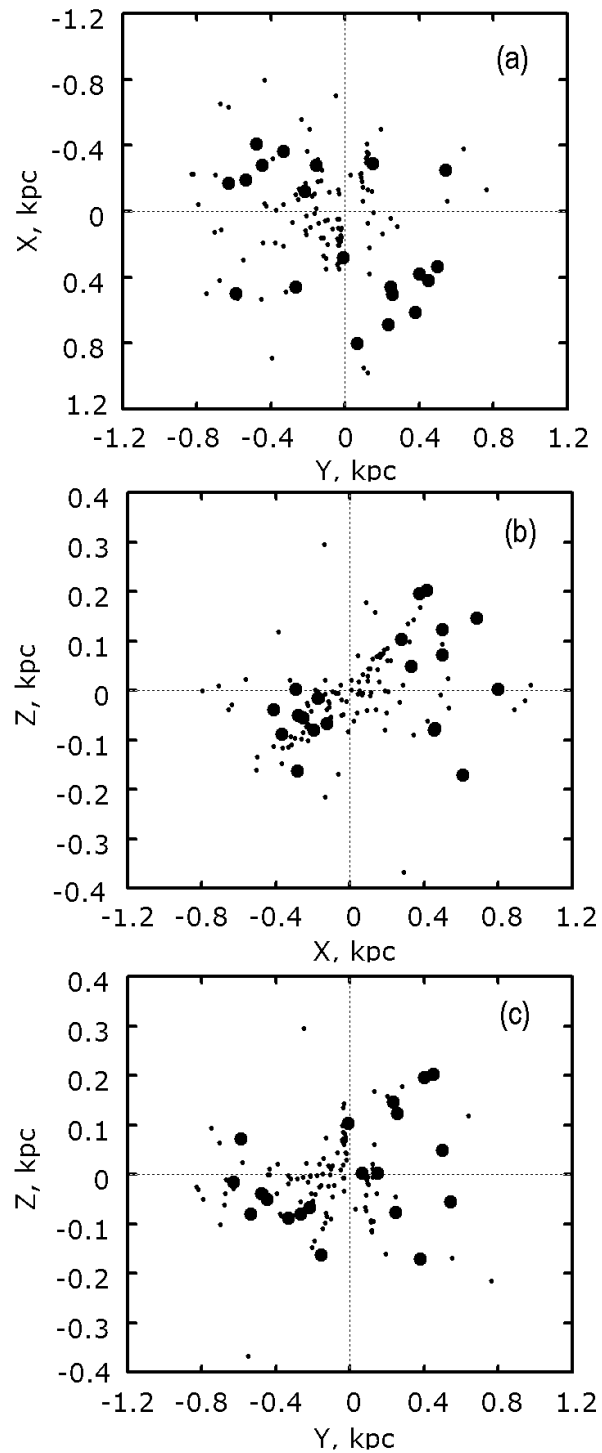Welsh, B.Y., Lallement, R., Vergely, J.-L. et al.: 2010, Astron. & Astrophys. 510, A54

Fig. 2 Distribution of 126 stars in Galactic planes XY (a); XZ(b) and YZ (c).
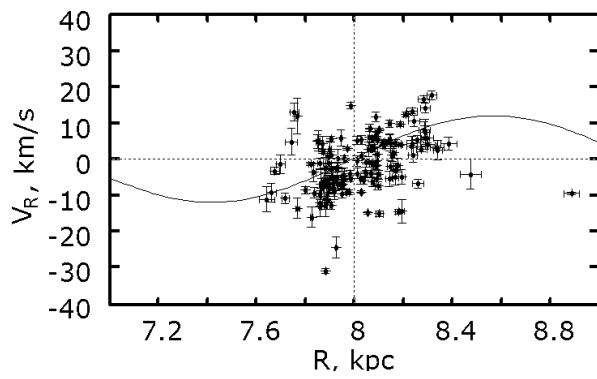
Fig. 3 Galactocentric radial velocities V_R of 147 HIPPARCOS stars of spectral classes O–B2.5, which distances are determined with errors $\sigma_\pi/\pi \leq 10\%$.